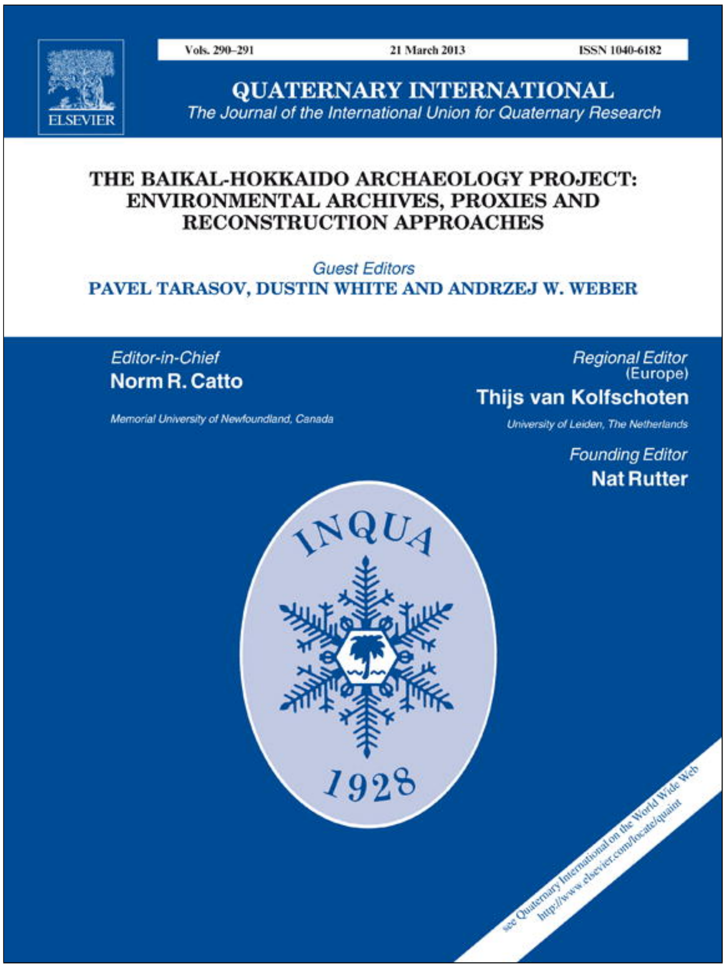
Vols. 290–291
21 March 2013
ISSN 1040-6182
ELSEVIER
QUATERNARY INTERNATIONAL
The Journal of the International Union for Quaternary Research
THE BAIKAL-HOKKAIDO ARCHAEOLOGY PROJECT: ENVIRONMENTAL ARCHIVES, PROXIES AND RECONSTRUCTION APPROACHES
Guest Editors
PAVEL TARASOV, DUSTIN WHITE AND ANDRZEJ W. WEBER
Editor-in-Chief
Norm R. Catto
Memorial University of Newfoundland, Canada
Regional Editor (Europe)
Thijs van Kolfschoten
University of Leiden, The Netherlands
Founding Editor
Nat Rutter
INQUA
1928
see Quaternary International on the World Wide Web
http://www.elsevier.com/locate/quaint

Quaternary International 290-291 (2013) 46–56

Contents lists available at SciVerse ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Multiproxy evidence for abrupt climate change impacts on terrestrial and freshwater ecosystems in the Ol'khon region of Lake Baikal, central Asia

Anson W. Mackay [a,*], Elena V. Bezrukova [b], John F. Boyle [c], Jonathan A. Holmes [a], Virginia N. Panizzo [a], Natalia Piotrowska [d], Alexander Shchetnikov [e], Ewan M. Shilland [a], Pavel Tarasov [f], Dustin White [g]

[a] *Environmental Change Research Centre, Department of Geography, UCL, Gower Street, London WC1E 6BT, UK*
[b] *Institute of Geochemistry, Russian Academy of Sciences, Siberian Branch, Irkutsk, Russia*
[c] *Department of Geography, The University of Liverpool, Roxby Building, Liverpool L69 7ZT, UK*
[d] *Institute of Physics, Department of Radioisotopes, GADAM Centre of Excellence, Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland*
[e] *Institute of Earth's Crust, Russian Academy of Sciences, Siberian Branch, Irkutsk, Russia*
[f] *Institute of Geological Sciences, Palaeontology, Freie University Berlin, Malteserstrasse 74-100, Building D, 12249 Berlin, Germany*
[g] *Archaeology, University of Southampton, Avenue Campus, Southampton SO17 1BF, UK*

A R T I C L E I N F O

Article history:
Available online 4 October 2012

A B S T R A C T

A palaeolimnological study of Lake Khall was undertaken to reconstruct impacts from five thousand years of climate change and human activity in the Ol'khon region of Lake Baikal. Taiga biome dominated regional landscapes, although significant compositional turnover occurred due to the expansion of eurythermic and drought resistant Scots pine. Climate during the mid-Holocene was wetter than the present, and Lake Khall was fresh, with abundant molluscs. By 4.4 cal ka BP, sedimentary geochemistry indicated a gradual change in lake water chemistry with an increase in lake salinity up to the present day, most likely controlled by groundwater influences. Vegetation turnover rate was highest between 2.75 and 2.48 cal ka BP, with the onset of drier, more continental climate, which resulted in an influx of aeolian particles to the lake. This abrupt shift was coincident with ice rafted debris event (IRD-2) in North Atlantic sediments and an attenuation of the East Asian summer monsoon. A second arid period occurred shortly afterwards (2.12–1.87 cal ka BP) which resulted in the decline in ostracod numbers, especially *Candona* sp. A rather more quiescent, warmer period followed, between 1.9 and 0.7 cal ka BP, with very little change in vegetation composition, and low amounts of detrital transfer from catchment to the lake. Peak reconstructed temperatures (and low amounts of annual precipitation) were concurrent with the Medieval Climate Anomaly. Between 0.77 and 0.45 cal ka BP, climate in the Ol'khon region became colder and wetter, although Lake Khall did not become fresher. Cold, wet conditions are seen at other sites around Lake Baikal, and therefore represent a regional response to the period concurrent with the Little Ice Age and IRD-0. After AD 1845 the region warms, and *Pediastrum* appears in the lake in high abundances for the first time. This increase is ascribed to nutrient enrichment in the lake, linked to the rapid increase in regional pastoral farming.

1. Introduction

Since 2001 a major interdisciplinary programme (Baikal Archaeology Project) has sought to characterise Holocene cultural dynamics among hunter-gatherer and pastoralist populations in central Asia (Weber et al., 2010). Results from this on-going research have redefined our understanding of hunter-gatherer adaptive strategies during the Neolithic–Bronze Age, including aspects of culture, subsistence and diet, mobility patterns, genetic structure, and social and political relations. Most of these new archaeological data have been derived from numerous well-preserved formal cemetery contexts, which have allowed detailed analyses of human skeletal remains. Focus has especially centred on a distinct bio-cultural discontinuity during the Middle Neolithic (Weber et al., 2002), and more recently the expansion of pastoralist populations (Nomokonova et al., 2010).

One of the oldest records of human occupation in this region (ca. 9 ka BP) was recorded at the Sagan-Zaba cove, in the Ol'khon

* Corresponding author.
E-mail addresses: a.mackay@ucl.ac.uk (A.W. Mackay), bezrukova@igc.irk.ru (E.V. Bezrukova), jfb@liverpool.ac.uk (J.F. Boyle), natalia.piotrowska@polsl.pl (N. Piotrowska), shchet@crust.irk.ru (A. Shchetnikov), ptarasov@zedat.fu-berlin.de (P. Tarasov), dustin.white@soton.ac.uk (D. White).

1040-6182/$ – see front matter © 2012 Elsevier Ltd and INQUA. All rights reserved.
http://dx.doi.org/10.1016/j.quaint.2012.09.031

region (known as *Priol'khon'e* in the Russian geographical literature) of Lake Baikal (Nomokonova et al., 2013). The white marble cliffs adjacent to the cove are world renown for their petroglyphs, dating as far back as 4 ka BP. Since the late Holocene, pastoralists dominated the Ol'khon region, herding a range of animals including cattle, sheep, goats and horses (Nomokonova et al., 2010). Subsistence patterns at Sagan-Zaba were more diverse than neighbouring regions, possibly because of the relatively harsh environment, such that, unusual for pastoralists, these populations also hunted *nerpa*, Lake Baikal's freshwater seal.

Despite the long history of prehistoric populations around Lake Baikal, there is very little evidence to suggest that they had a significant impact on regional landscapes (Tarasov et al., 2007). However, the pollen source area of Lake Baikal is vast and indicative of very broad regional-scale variability (Sugita, 1994), such as biomes (Seppä and Bennett, 2003; Tarasov et al., 2007). One would not necessarily expect Lake Baikal sediments to record impacts from regional prehistoric populations. Smaller lakes have smaller source areas (Jacobson and Bradshaw, 1981), and therefore potentially offer a better possibility for disentangling natural (e.g. climatic) from anthropogenic impacts. Around Lake Baikal, smaller lakes are increasingly being investigated (e.g. Tarasov et al., 2009; Ptitsyn et al., 2010; Mackay et al., 2012), although very few studies have looked at palaeoenvironmental changes in the semi-arid region to the west of the lake (Sklyarov et al., 2010).

The principal aim of this study is to provide a detailed palaeolimnological record of environmental change in the climatically sensitive Ol'khon region of Lake Baikal, where there is a long, dynamic history of human occupation.

2. Geology and regional climate

The study area lies to the south of Ol'khon Island on the west coast of Lake Baikal and is represented by Paleozoic Ol'khon metamorphic terrane (Sklyarova et al., 2002). The flat-topped Ol'khon Island and Ol'khon region form part of the Middle Baikal inter-basinal link. Small grabens and horsts shape the link's surface and form linear en-echelon systems. The grabens are confined to two types of recent faults in the process: northeast linear faults inherited from the Early Paleozoic structures and north-northeast pull-apart structures related to late left-lateral strike-slip dislocations of the Baikal rift formation. Numerous fresh and salt-water lakes are associated with these faults (Sklyarova et al., 2002), with their long-term existence being dependent on faults draining deep, ground-water horizons (Sklyarov et al., 2010). The study site, Lake Khall, is located on marble and surrounded by two intrusions – Birkhinsky in the north (gabbro, gabbro-norites, olivine gabbro) and Tsagan-Zabinsky in the south (andesites, andesite-basalts and basalts). It is a shallow, isometric, freshwater bicarbonate lake located in a structural low of one of these northeast linear faults. Lake Khall is probably fed from subaqueous groundwater, and so its chemical composition reflects the chemistry of the feeder groundwater (Sklyarova et al., 2002). The region is arid to semi-arid because it sits in the rain shadow of the neighbouring Primorsky Mountain Range (Fig. 1). Annual precipitation is low between 200 and 350 mm/yr (Atlas Baikala, 1993). Vegetation is therefore a mixture between light coniferous taiga forest with fragmented steppe landscape, including the Tazheran steppes (Sklyarov et al., 2010).

3. Methods

Fieldwork took place on 26th July 2006. pH and conductivity were measured *in situ* using a Fisher Scientific accumet AP85 pH/conductivity meter. The pH of the surface water was 9.0 pH units, and conductivity was 790 μS/cm. Due to time constraints, it was not possible to conduct a detailed bathymetry of the lake, although a Plastimo Echotest II handheld depth sounder was used to estimate the deepest region at 3.10 m, from where coring was undertaken. A 71 mm diameter Livingstone core was initially extracted (44 cm length), which maintained the surface sediment–water interface, followed by a second overlapping Livingstone drive of 91 cm. Core location co-ordinates were 106°25′50.70″E, 52°41′14.54″N.

3.1. Chronology

Extracted lake sediments were highly humified and from many levels it was not possible to obtain sizeable plant macrofossils for radiocarbon analyses. Radiocarbon dating of humified sediments was instead performed on total organic carbon (TOC) from 5 bulk sediment samples. *Potamogeton* seeds were isolated from a further four levels. All nine samples were radiocarbon dated using accelerator mass spectrometry (AMS) at the Poznan Radiocarbon Laboratory, Poland (Goslar et al., 2004) (Table 1). The amount of radiocarbon reservoir effect (i.e. shift towards older ages) was estimated on the basis of ^{14}C dating contemporary leaf sample of *Potamogeton* from the littoral region of Lake Khall. The result of 105.58 ± 0.33 pMC suggests a reservoir age of 100–200 years (Table 1). We have therefore added the reservoir correction of 150 ± 50 years to the age model for Lake Khall sediment core.

Calibration of radiocarbon dates was undertaken using the Intcal09 calibration curve (Reimer et al., 2009). The calibration was performed by "Bacon" software simultaneously to building the calendar age scale for the whole core. In order to produce the age-depth model this programme simulates the accumulation of deposit through small random increments, and also takes into account the limitations on accumulation rate and its variability

Table 1
Results of AMS radiocarbon dating for Lake Khall sediment core. Depth range and mid-depth are the original depths of samples from core. Calibration of independent ^{14}C dates from the core was performed using IntCal09 radiocarbon calibration curve (Reimer et al., 2009) and OxCal software ver. 4.1.7 (Bronk Ramsey, 2009), assuming the reservoir correction of 150 ± 50 years.

Sample code	Sample material	Depth range, cm	Mid-depth, cm	^{14}C age BP	Calibrated age range cal BP (68.2%)		Calibrated age range cal BP (95.4%)	
Poz-25686	Contemporary macrophytes	n/a	n/a	105.58 ± 0.33 pMC	n/a	n/a	n/a	n/a
Poz-30449	TOC	20–21	20.5	555 ± 30	626	532	640	519
Poz-25740	*Potamogeton* seed	24–24.5	24.25	345 ± 30	465	319	485	313
Poz-25682	*Potamogeton* seed	40–40.5	40.25	330 ± 30	455	316	474	308
Poz-30448	TOC	40–41	40.5	1140 ± 30	1072	980	1169	968
Poz-33695	TOC	50–51	50.5	2110 ± 35	2131	2009	2295	1992
Poz-30447	TOC	60–61	60.5	2105 ± 30	2123	2010	2150	1995
Poz-33696	TOC	71–72	71.5	2605 ± 35	2759	2724	2787	2545
Poz-25683	*Potamogeton* seed	80–81	80.5	4285 ± 35	4865	4835	4964	4822
Poz-25684	*Potamogeton* seed	90–91B	90.5	4930 ± 70	5730	5596	5892	5487

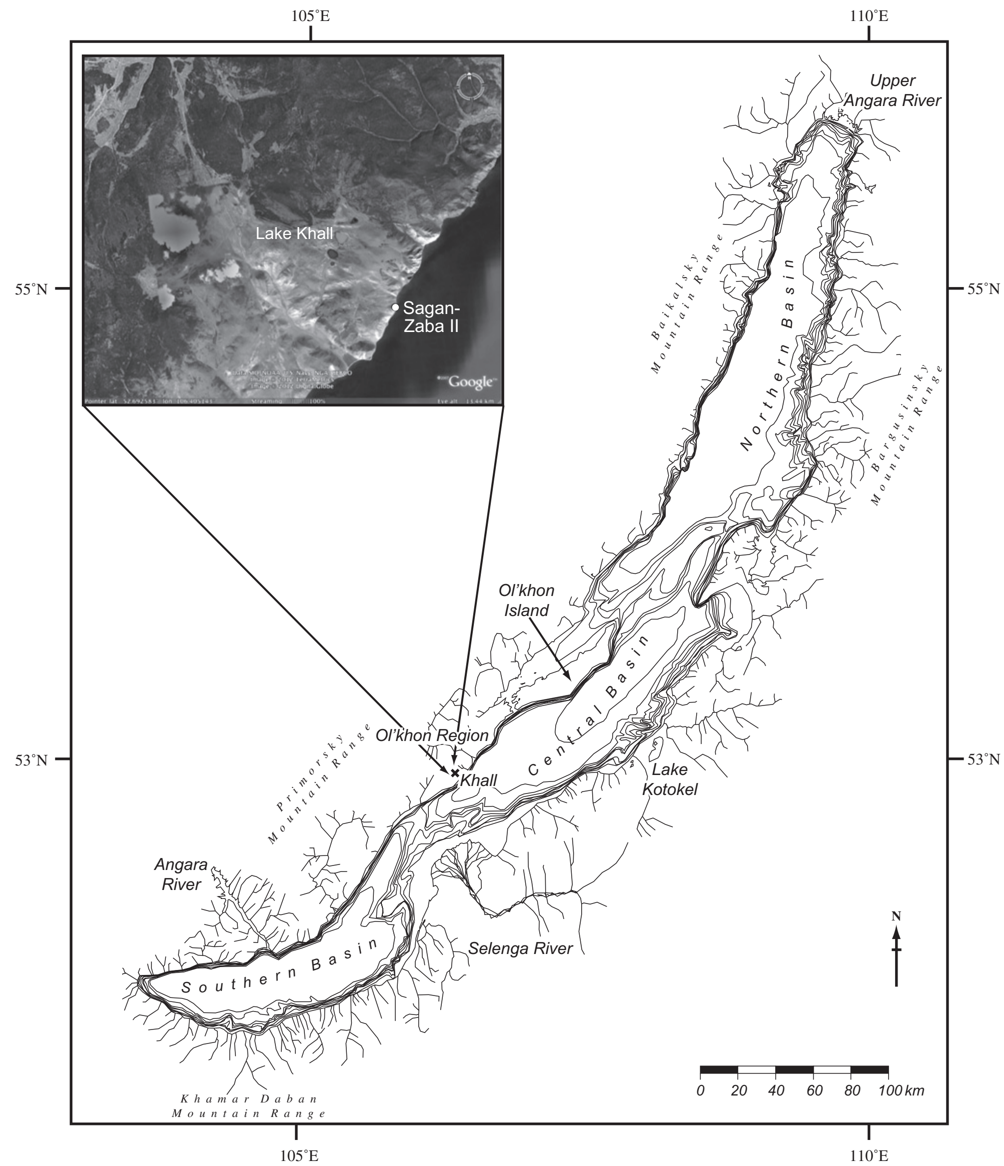

Fig. 1. Map of Lake Baikal and its immediate catchment, showing the location of key sites: Lake Khall, Ol'khon region, Lake Kotokel and Primorsky mountain range.

(Blaauw and Christen, 2011). Although some of the obtained ^{14}C dates can clearly be regarded as outliers, all results of radiocarbon dating were included in the modeling performed for Lake Khall. Additionally, the sampling year AD 2006 was assigned to the depth 0 and AD 1963 at 6.25 cm, identified on the basis of ^{137}Cs peak. The age-depth model was calculated with 20 sections. The *a priori* information for accumulation rate was set as a gamma distribution with mean 30 yrs/cm and shape 2, and a beta distribution with strength 4 and mean 0.7 was fixed for the accumulation variability, following the recommendation by Blaauw and Christen (2011). The age-depth model resulting from 2,640,000 iterations is presented in Fig. 2.

The uppermost 36 cm of sediment were also dated using ^{210}Pb, a naturally-produced radionuclide that has been extensively used in the dating of recent sediments (Appleby, 2001) and ^{137}Cs, an artificially produced radionuclide, introduced to the study area by atmospheric fallout from nuclear weapons testing. Core sub-samples were counted on a Canberra well-type ultra-low background HPGe gamma ray spectrometer to determine the activities of ^{210}Pb, ^{137}Cs and other gamma emitters. Spectra were accumulated using a 16 K channel integrated multichannel analyzer and analysed using the Genie 2000 system. Energy and efficiency calibrations were carried out using bentonite clay spiked with a mixed gamma-emitting radionuclide standard, QCYK8163, and checked against an IAEA marine sediment certified reference material (IAEA 135). The $^{210}Pb_{excess}$ activity was estimated by subtraction of the average value of ^{210}Pb activity in deeper core samples (14 Bq/kg), where total ^{210}Pb activities had fallen to virtually constant values and so approximate the "background" or supported ^{210}Pb activity. Sediment accretion rates were determined using the Constant Flux, Constant Sedimentation (CF–CS) model of ^{210}Pb dating, where the sedimentation rate is given by the slope of the least squares fit for the natural log of the $^{210}Pb_{excess}$ activity versus depth (Krishnaswami et al., 1971; Robbins, 1978).

3.2. Pollen analysis

Twenty-nine 1 cm^3 sediments were processed for pollen analysis using standard laboratory methods, including HCl and KOH treatments, heavy-liquid separation and subsequent acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). Pollen and spores were mounted in glycerin and counted using light microscopy

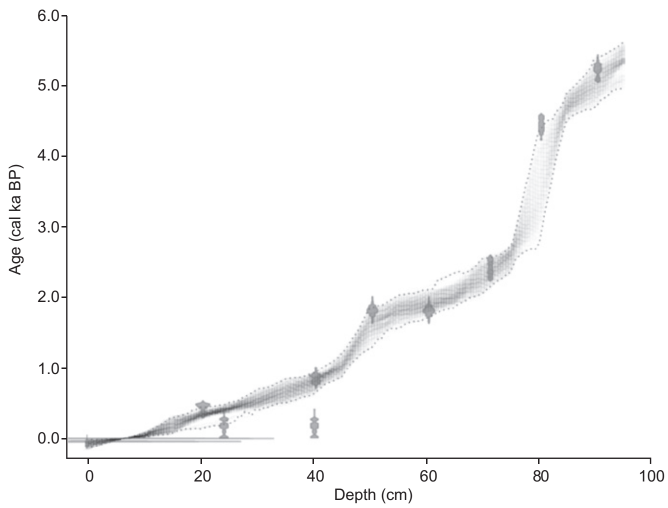

Fig. 2. Age-depth model based on ^{137}Cs and calibrated radiocarbon AMS dates, constructed using 'Bacon' (Blaauw and Christen, 2011). Grey-shaded area represents 95% confidence intervals of modelled ages (black line).

at ×400–×1000 magnification. Identification of fossil pollen and spores was assisted with the use of regional pollen atlases (Kuprianova and Alyoshina, 1972; Bobrov et al., 1983; Moore et al., 1991) and the reference collection held at the Institute of the Earth Crust, Irkutsk. Between 176 and 518 terrestrial pollen grains were counted at each level (304 on average). Relative abundances of individual taxa were based on the sum of all terrestrial pollen grains. *Haploxylon*-type pine pollen (*Pinus sibirica*, *Pinus pumila*) was separated from *Diploxylon*-type pine pollen (*Pinus sylvestris*) based on the position of the sacci in polar view. *Pediastrum* coenobia colonies contain sporopollenin which allowed us to count them alongside pollen (e.g. Nielsen and Sørensen, 1992). *Pediastrum* relative abundances were calculated in relation to the total sum of terrestrial pollen. We used the pollen-based biome reconstruction method and equation presented in Prentice et al. (1996) and a regionally approved biome-taxon matrix (Tarasov et al., 2009; Bezrukova et al., 2010), which assigns all selected pollen taxa to appropriate biomes. All terrestrial pollen taxa from Lake Khall sediments were assigned to regional plant functional types (PFTs) and biomes – see Tarasov et al. (2009) for full details. Quantitative climate reconstructions were performed using best modern analogue (BMA) approach (Overpeck et al., 1985; Guiot, 1990) previously applied to the Holocene pollen records from Lake Baikal (Tarasov et al., 2007) and Lake Kotokel (Tarasov et al., 2009). A reference modern dataset based on the global climate averages (New et al., 2002) and extensive modern surface pollen data from northern Eurasia, with a good representation of the Lake Baikal region (see Tarasov et al., 2005 for details). Reconstructions undertaken were annual precipitation (Pann), mean July temperatures (*T*w, also referred to here as mean temperature of the warmest month), and mean January temperature (*T*c, also referred to here as mean temperature of the coldest month).

3.3. Ostracods

Forty samples were processed for ostracod determinations. Wet sediment samples were dispersed in tap water overnight and then gently sieved through a 250 μm mesh. The coarse residues were dried at 105 °C. All of the ostracod shells were picked from these residues under a low-power binocular microscope using a fine (4/0) moistened paintbrush, sorted into taxonomic groups and stored in micropalaeontological slides. Results are expressed in numbers of valves per unit weight of sediment.

3.4. Mineral magnetics

At least 1.5 g of freeze-dried sediment from forty-one samples was packed into plastic magnetics sample pots. Low-frequency and high-frequency magnetic susceptibility was measured for each sample using a Bartington MS2 Magnetic Susceptibility meter.

3.5. Particle size

Particle-size analysis was undertaken on the <2 mm fraction of sediment from 40 samples. In practice, most of the sediment from the core was less than 2 mm diameter, so the grain-size analyses are essentially bulk-sample determinations. Each sample was dispersed in water, sieved through a 2 mm mesh and then disaggregated ultrasonically prior to analysis using a Malvern Mastersizer laser particle-sizer. The results were processed using GRADISTAT (Blott and Pye, 2001). For plotting purposes, we used the grain-size statistics produced from the Folk and Ward (1957) method.

3.6. X-ray fluorescence (XRF) spectrometry analysis

Up to 2 g of freeze-dried sediment was finely ground and compressed into 25 mm deep polythene sample pots for XRF analysis of 41 samples. Samples were subjected to gamma photons from a silicon (lithium) semi-conductor detector for 240 s each, using a Spectro Xlab 2000 energy dispersive XRF spectrometer. Calibration was conducted with two known sediment standards of Buffalo River Sediment.

3.7. Statistical analyses

Detrended correspondence analysis (DCA) was initially undertaken to establish the magnitude of vegetation turnover. Relative abundance data were log $(x + 1)$ transformed in order to stabilize species variance and rare species were down-weighted. The axis 1 gradient length (standard deviation units) was 1.049, indicating that linear ordination techniques were more appropriate for analyses. Principal components analysis (PCA) with symmetric scaling of the ordination scores to optimise scaling for both samples and species was undertaken (Gabriel, 2002). Species data were log $(x + 1)$ transformed and both species and samples were centred to give a log-linear contrast PCA, appropriate for closed relative abundance data (Lotter and Birks, 1993). XRF data were analysed using PCA with samples centred and standardised. Significance of PC axes was tested with a broken stick model (Jollifer, 1986) using BSTICK v1.0 (Line and Birks, 1996). Compositional change in the palynological data (β-diversity) was estimated using detrended canonical correspondence analysis (DCCA) with the data constrained using dates obtained from the age-depth model (Birks, 2007). All ordination analyses were undertaken using Canoco v. 4.5 (ter Braak and Šmilauer, 2002). Monte Carlo permutation tests for temporally ordered data were used to determine significance levels ($n = 499$). Stratigraphical profiles were constructed using C2 Data Analysis Version 1.5.1 (Juggins, 2007). Stratigraphical zones for each proxy were delimited by optimal partitioning (Birks and Gordon, 1985) using the unpublished programme ZONE (version 1.2) (Juggins, 1991).

4. Results

4.1. Core description and chronology

The core consisted mainly of homogenous, silty clay sediment between 0 and 76 cm (colour 5Y-4/1-2), with the bottom sediments (76–91 cm; colour 10 YR-3/1) packed full of broken bivalve shells.

The age-depth model for Lake Khall shows that the core spans the past ca. 5.2 cal ka BP (i.e. calibrated years before AD 1950, taken as present, are consistently used) (Fig. 2). Although the sedimentation rate was temporally variable, some distinct sections can be distinguished, for which the sedimentation rate was relatively constant. For the uppermost section from 0 to 8 cm (ca. 10 cal BP) the average sedimentation rate derived from the Bacon model was 1.48 $\pm$ 0.25 mm/year, which is in accordance with the number obtained on the basis of ^{210}Pb measurements (1.11 $\pm$ 0.44 mm/year). The mean accumulation rate for the section between 8 cm (10 cal BP) and 74 cm (ca. 2.6 cal ka BP) was 0.36 $\pm$ 0.02 mm/year. The oldest part of the sediment was characterized by lower sedimentation rate, 0.16 $\pm$ 0.043 mm/year.

4.2. Pollen stratigraphy

Taiga was the dominant biome throughout the sequence (Fig. 3) suggesting the record reflects the regional 'forest' signal rather than only the local 'steppe' one. Compositional turnover in the palynological data was high (β-diversity = 1.281), although greatest change occurred between 5.15 and 2.48 cal ka BP, with a very rapid change between 2.75 and 2.48 cal ka BP (Fig. 6). Between 1.76 and 0.84 cal ka BP there was very little change in vegetation composition, but variability increased markedly from ca. AD 1800 to the present. Only PCA axis 1 was significant and accounted for 71.1% of variation in the species data. Three zones were delimited within the pollen stratigraphy (Fig. 3).

- Khall-3 (91–73.5 cm; 5.15–2.61 cal ka BP) was characterised by highest abundances of *Betula* sect. *Albae* (25–50%) and *Artemisia* (10–19%). *P. sibirica* percentage values, initially very high at the very base of the profile (25%), declined abruptly to 3% and then increased to 10–13% again. *P. sylvestris* was initially present in only very low abundances (3–4%) at the base of the profile and quickly increased, reaching up to 36–41% in upper part of this zone. *Picea obovata* and *Alnus fruticosa* reached their highest values (up to 5%) in this zone.
- Khall-2 (73.5–13.25 cm; 2.61–0.15 cal ka BP [ca. AD 1800]) was dominated by *P. sylvestris* pollen, with values fluctuating between 60–84%. *P. sibirica* was also well represented (10–25%), and contribution from *Artemisia* varied between 0.5 and 9%. *A. fruticosa* pollen was absent or present in low abundances. *Picea* percentages were also generally low and did not exceed 3%.
- Khall-1 (13.25–0 cm; ca. AD 1800 – AD 2006) had a pollen composition similar to Khall-2, with slightly lower and fluctuating percentage values of *P. sylvestris* and slightly higher abundances of *B.* sect. *Albae* and Cyperaceae pollen. Within this zone *Pediastrum* algae spores appeared for the first time in the record, and rapidly increased to very high abundances.

4.3. Ostracods

We only present preliminary results here: detailed taxonomic and palaeoecological accounts of the ostracod assemblages will follow in a future publication. The ostracod assemblages were of fairly low diversity (<10 species in total) and dominated by a member of the genus *Limnocythere*, which has yet to be identified to specific level (Fig. 4). Other taxa present include *Candona* spp., *Pseudocanodona* spp., *Cyclocypris* sp., *Cypris* sp., *Ilyocypris* sp. and *Potamocypris* sp. as well as several others that remain unidentified. In most of the core levels examined, adult and juvenile shells were found. Concentrations varied from about 300 to less than 2 valves per gram of sediment. Concentrations were greatest in the basal 10 cm of the core, declining above this. Candonids were absent above 2.10 cal ka BP. A varying proportion of the valves displayed a black coating. Energy dispersive spectroscopy (EDS) analysis under a scanning electron microscope

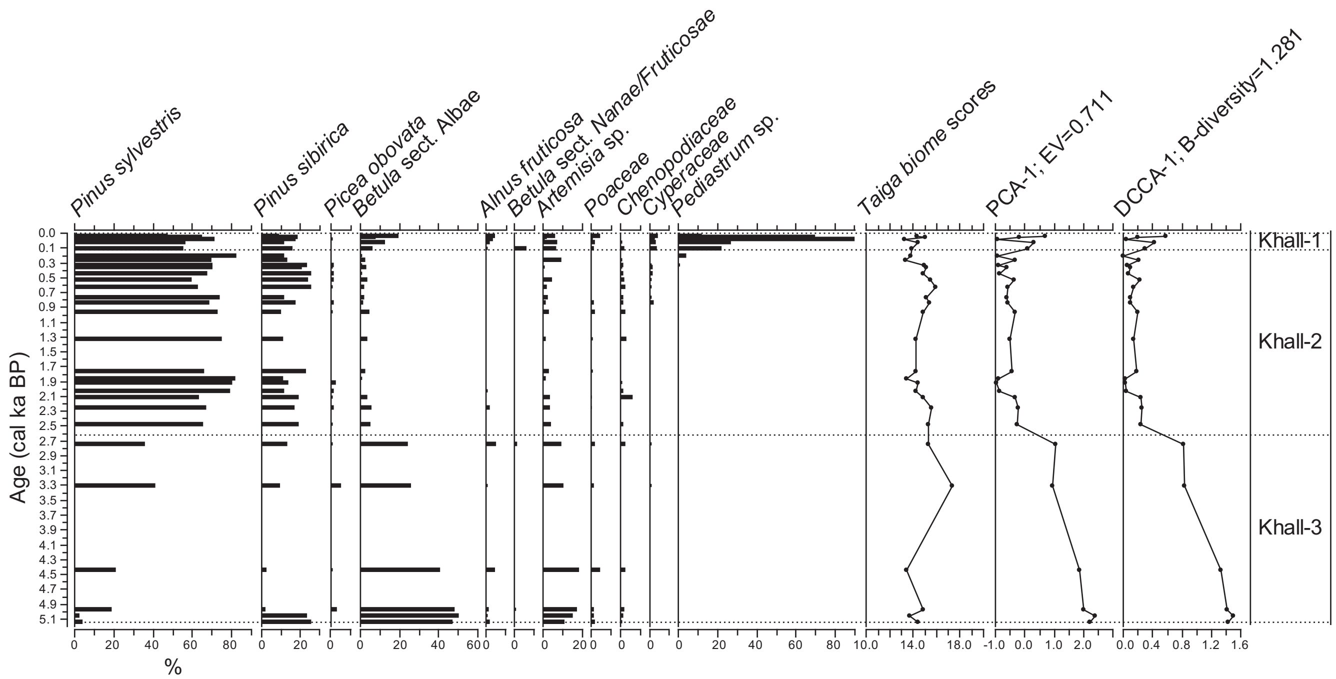

Fig. 3. Pollen, spore and *Pediastrum* coenobia colony relative abundances plotted on the calibrated age scale. Taiga biome scores are also shown – see Section 3.2 for details. Significant PCA axis 1 sample scores (+eigenvalue; EV) and significant compositional turnover (beta diversity; SD units) value for vegetation data is also given ($p = 0.05$; $n = 499$). Pollen zones have been delimited using optimal partitioning.

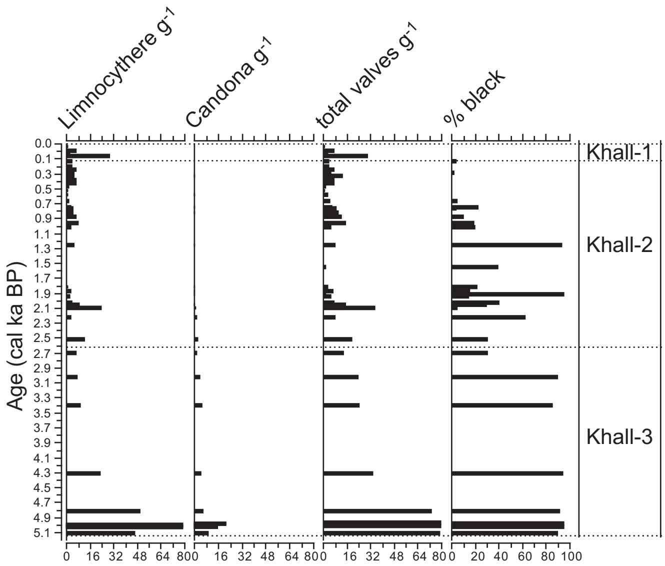

Fig. 4. Total ostracod concentrations (valves/g) are plotted on the calibrated age scale, along with the two most abundant genera *Lymnocythere* sp. and *Candona* sp. The concentration of blackened valves is also given.

suggested that the coating was non-metallic but laser Raman determinations were inconclusive.

4.4. Mineral magnetics

Low field magnetic susceptibility measurements ranged between 0.1 and 4.7 10^{-5} SI (Fig. 5). Values increased by small amount from the base of the core up to ca. 2.8 cal ka BP (2–2.6 10^{-5} SI). There was a substantial increase in values between ca. 2.6–2.1 cal ka BP from 2.6 to 4.3 10^{-5} SI. Values showed almost no change between 1.4 and 1.0 cal ka BP, after which they declined to the top of the profile, with very rapid decline after AD 1800.

4.5. Particle size

Mean particle size (Mz; μm) ranged between 12.7 and 48.3 μm (mean = 20.6; median 17.6). Five peaks greater than mean Mz occurred at 5.12, 2.52, 1.88, 0.79 cal ka BP and AD 1925 (Fig. 5). Sorting of the grain size distributions ranged between 3.2 and 7.1 μm (mean = 3.9; median 3.7). Five sorting peaks greater than the mean occurred at identical times as peaks in Mz. Almost all skewness values were negative (mean = −0.1; median = −0.1), except for 5 positive values that occurred at the same times as high values for mean grain size and sorting. Kurtosis (mean = 1.0; median = 1.0) exhibited a different pattern from other grain size parameters. Values were above average between 5.12 and 3.03 cal ka BP, and declined to lowest value at 2.52 cal ka BP, when values of other particle size proxies increased. But peaks in kurtosis did co-occur at 1.88, 0.79 cal ka BP and 1925 AD.

4.6. XRF spectrometry analysis

Selected elements are presented in Fig. 7. Ti, Al and K increased from 5.08 cal to 1.80 cal ka BP. Between 1.80 and 0.80 cal ka BP values showed little variation, and then they declined up to ca. AD 1950. The rate of decline increased at the top of zone Khall-2, from 0.12 ka BP, concomitant with rapid increase in sedimentation rate and decline in magnetic susceptibility values. Only PCA axis 1 was significant, accounting for 73.8% of variance in geochemical data. This axis was driven by a strong gradient between high Ca and Sr concentrations at the bottom of the core, and high concentrations of most other elements between ca. 1.90–0.50 cal ka BP (notably Fe,

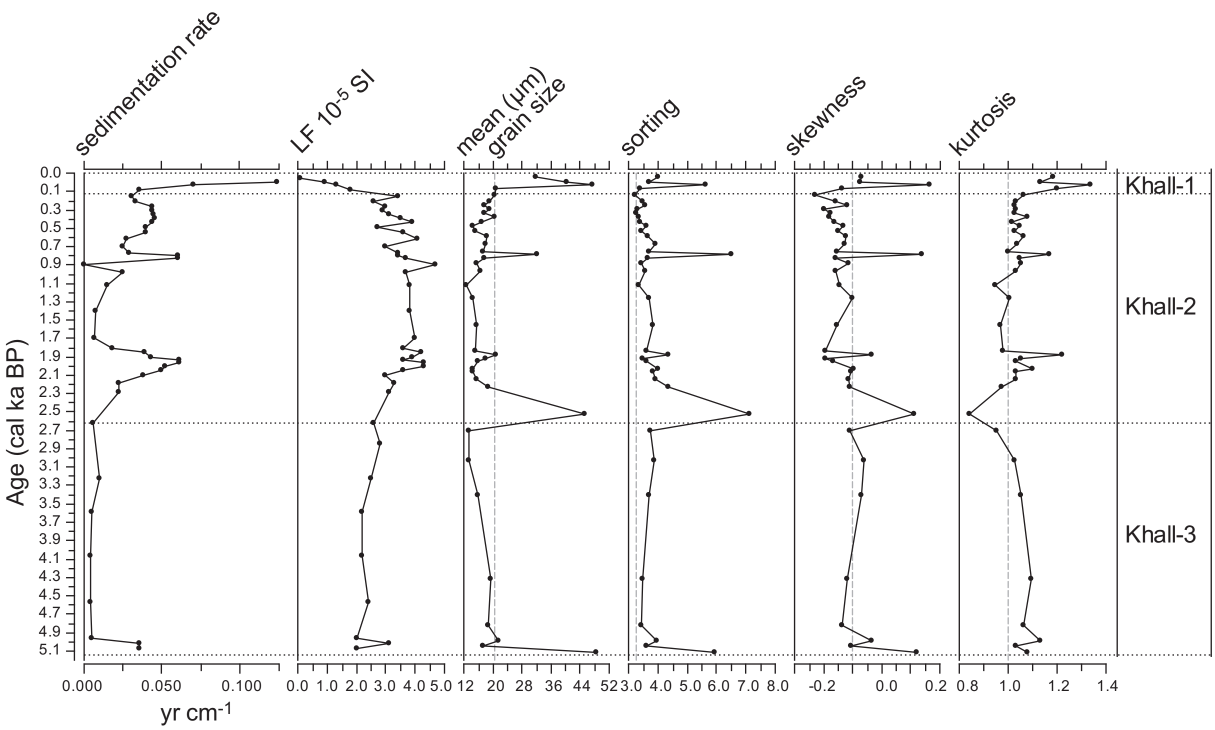

Fig. 5. Low-frequency magnetic susceptibility measurements and particle size statistics produced from Folk and Ward (1957) method (mean particle size, sorting, skewness and kurtosis). Sedimentary mean values are shown with a vertical line for each of mean particle size, sorting, skewness and kurtosis.

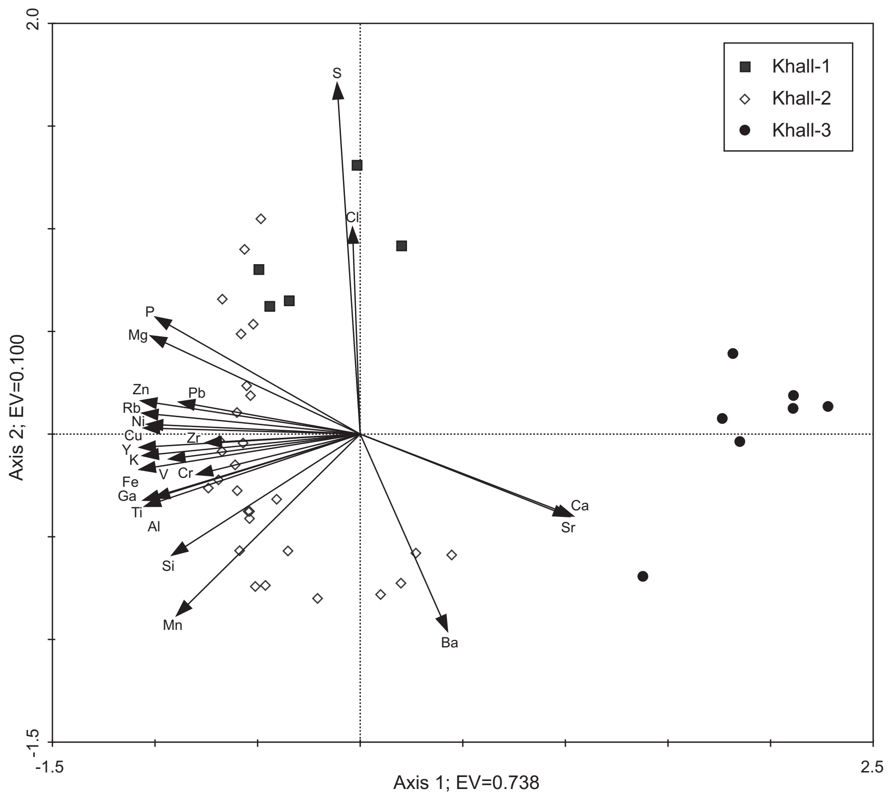

Fig. 6. PCA biplot of geochemical data. Axis 1 is plotted against axis 2. Axis 1 accounts for significant 73.8% variation in element data. Axis 2 accounts for only 10.0% variation in the data which broken stick shows is not significant.

Y, Zn, Rb, K, Ti, Cu and Al) (Fig. 6). Although axis 2 was insignificant, elevated concentrations of S and Cl were especially abundant in the uppermost sediments.

5. Discussion

Taiga biome dominated the vegetation reconstruction from the Ol'khon region since at least 5.2 ka BP. However, compositional turnover was very significant; β-diversity values were considerably higher than for longer Holocene sequences in other boreal regions such as southern Norway (Birks, 2007) and the eastern Sayan Mountains (Mackay et al., 2012). This suggests that the semi-arid, Ol'khon region was more sensitive to climate variability and environmental change than other boreal regions with higher precipitation. Such sensitivity was responsible for major directional shifts during the past 5.2 cal ka in Lake Khall and the surrounding region. DCCA and zonation analyses delimited most rapid periods of vegetation change at 2.74–2.48 cal ka and after AD 1800. Pollen assemblage composition showed a progressive decrease in birch pollen and shift to a predominance of Scots pine pollen between 5.15 and 2.48 cal ka, which drove overall compositional turnover. Scots pine produces vast amounts of pollen, and once established, it dominates pollen assemblages. The numerical scores of the taiga biome (Fig. 3) demonstrated minor fluctuations, but did not show decreasing or increasing trend through the whole record. Therefore, the increase in arboreal pollen percentages between 2.75 and 2.48 cal ka BP likely does not imply greater regional afforestation, nor any decrease in steppe communities, but are indicative of change in forest composition, with the spread of eurythermic and drought resistant Scots pine rather than noticeable spread in regional woody cover. These findings are in line with the woody cover reconstruction derived from Lake Kotokel pollen records on the opposite shore of Lake Baikal (Fig. 1) (Tarasov et al., 2009; Bezrukova et al., 2010).

5.1. Mid-Holocene environmental change

Up to 4.5 cal ka BP, forest-steppe communities dominated local vegetation in Ol'khon region, especially tree birches (*Betula* sect. *Albae*), *Artemisia* and Chenopodiaceae taxa. Reconstructed temperature of the coldest month and annual precipitation were highest during this period. Owing to the lack of formal identification of the ostracod species, interpretations of the assemblages remain circumspect at this stage, although we can say that assemblages were deposited *in situ*, because in most of the core levels examined, both adult and juvenile shells were found. However, candonids generally only tolerate low salinity waters (Holmes et al., 2010) and the Lake Khall assemblage suggests that the lake was fresher in the past. The geochemical record also provides evidence for a fresher lake in the past; low Sr/Ca ratios indicate low lake-water salinity (Marshall, 1969). Detrital transport from the catchment into the lake is represented by e.g. Ti, Al and K, and these elements were lowest when precipitation was highest. Ca on the other hand may come from both authigenic production within the lake and from detrital flux (e.g. Wünneman et al., 2010). In order to distinguish between these two processes we use the Ca/Al ratio, which at the base of the core was very high (60), indicative of high authigenic production. High production occurs at the same time as highest concentrations of ostracods, and shell remains of a, as yet unidentified, bivalve. We have as yet to characterise mineralogy of the sediments (e.g. using XRD) but low K/Rb and high Ti/K ratios suggest dominance of clays and micas, although feldspars became more important after 3.59 cal ka BP. Elsewhere in the Lake Baikal region, other records of pollen-inferred annual precipitation were also high (e.g. Tarasov et al.,

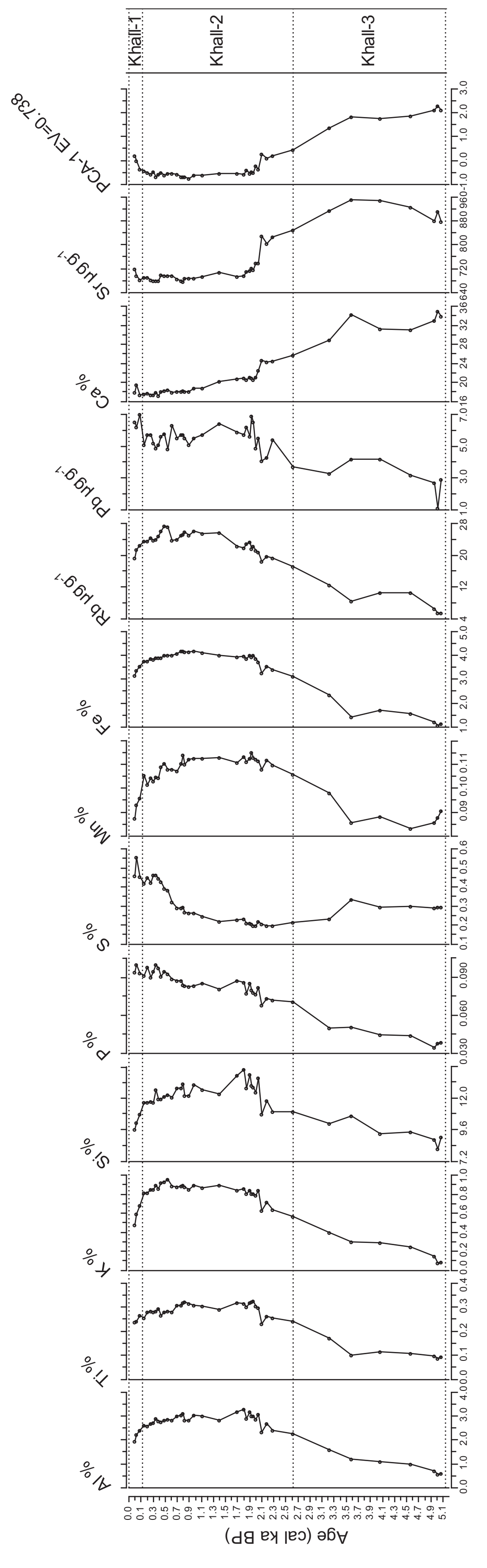

Fig. 7. Geochemical stratigraphy of Lake Khall. Selected major elements are shown, expressed either as percentages (Al, Ti, K, Si, P, S, Mn, Fe) or concentrations (μg/g: Rb, Pb, Ca, Sr). Significant PCA axis 1 sample scores (+eigenvalue; EV) are also shown.

2007; Tarasov et al., 2009), as was isotopic evidence for elevated precipitation-dominated discharge into Lake Baikal (Mackay et al., 2011, Fig. 8). Further afield, isotopic records from Dongge Cave in southern China (Fig. 8) were indicative of strong East Asian Summer Monsoon (EASM) linked to relative high summer insolation (Wang et al., 2005).

Between ca. 4.4–2.8 cal ka BP, the pollen record is poorly resolved. However, there was a significant expansion of Scots pine (*P. sylvestris*) and, to a lesser extent, Siberian pine (*P. sibirica*) (a major component of dark, coniferous taiga), concomitant with a decline in deciduous forest. The expansion of Scot's pine occurred substantially later than at neighbouring regions e.g. Lake Hovsgöl (10.0 cal ka BP; Prokopenko et al., 2007), Altai Mountains, (9.5 cal ka BP, Blyakharchuk et al., 2004), Eastern Sayan Mountains (9.1 cal ka BP, Mackay et al., 2012), southern Lake Baikal (7 cal ka BP, Demske et al., 2005) and Lake Kotokel (ca. 6.9–6.4 cal ka BP Bezrukova et al., 2008; Shichi et al., 2009). The expansion of Scots pine in Ol'khon is in close agreement with the expansion of Scots pine to the north of Lake Baikal (5.2 cal ka BP, Bezrukova et al., 2006), highlighting that distinct regional differences exist in the spread of conifer forest to coastal regions of Lake Baikal. The period of conifer expansion in Ol'khon region occurred during a period of increasing aridity, as inferred from several of the proxies studied. For example, Sr/Ca ratios indicate a progressive increase in salinity of Lake Khall, likely linked to reductions in pollen-inferred precipitation anomalies, while pollen-inferred temperatures remained above values experienced in recent decades (Fig. 8). Detrital input (inferred from Al, Ti and K) also increased at this time. Given the similarity between PCA of the vegetation and geochemistry, it is likely that both were influenced by the same drivers. Elsewhere, $\delta^{18}O_{diatom}$ showed a marked decline during this period, indicative of a decline in the proportion of rain-fed discharge into Lake Baikal (Mackay et al., 2011, Fig. 8). The shift to a more arid climate was also reflected further afield in the weakening of the EASM (Wang et al., 2005, Fig. 8).

5.2. Abrupt environmental change

Compositional turnover in vegetation communities was greatest between 2.75 and 2.48 cal ka BP, which continued to change up to 1.87 cal ka BP, linked to the maximum expansion of dark coniferous taiga. Particle size characteristics in Lake Khall show that they were generally very poorly sorted, i.e. they had not undergone efficient sorting before their burial into the bottom sediments, which is common for shallow lakes (Mischke et al., 2010). One of the largest peaks in mean particle size occurred at 2.52 cal ka BP, which was likely caused by strong aeolian influx because these large particles were also extremely unsorted (Fig. 5). Pollen-inferred annual precipitation anomalies dropped rapidly, and values remained low, below that of the present day, for much of the remainder of the Holocene (Fig. 8). There was also a marked decline in mean temperature of coldest month, while mean temperatures of the warmest month increased. The climate in the Ol'khon region therefore became more continental. The start of these climatic and vegetation changes are coincident with a peak in ice rafted debris material in North Atlantic sediments (IRD-2; Bond et al., 1997), which also resulted in low $\delta^{18}O$ isotopic values in Lake Baikal and in Dongge cave, indicative of a decline in proportion of rain-fed discharge into Lake Baikal (Mackay et al., 2011) and an attenuated EASM (Wang et al., 2005) respectively.

Between 2.12 and 1.87 cal ka BP there was a significant decline in mean annual precipitation and mean temperature of the coldest month but an increase in mean temperature of the warmest month (Fig. 8). Drier, more continental climate resulted in peak abundance of Scots pine, which drove compositional turnover in the Ol'khon region. An increase in Sr/Ca ratio suggested that chemical

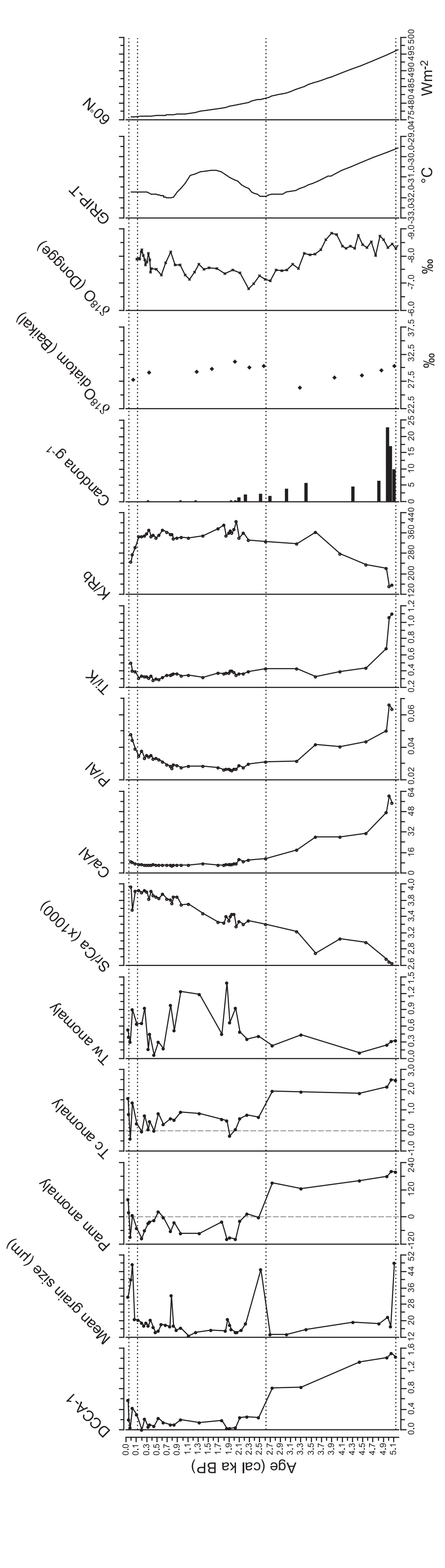

Fig. 8. Composite stratigraphical plot showing: (i) pollen DCCA axis 1 sample scores; (ii) mean grain size; (iii) pollen-inferred reconstruction anomalies (total annual precipitation – Pann; mean temperature of the coldest month – *Tc*; mean temperature of the warmest month – *Tw*); (iv) geochemical ratio of selected elements Sr/Ca (×1000), Ca/Al, P/Al, Ti/K, K/Rb; (v) concentrations of *Candona* sp.; (vi) oxygen isotope data from Lake Baikal biogenic silica (Mackay et al., 2011); (vii) oxygen isotope data from Dongge Cave, southern China (Wang et al., 2005); (viii) palaeo-temperatures inferred from the GRIP borehole (°C) (Dahl-Jensen et al., 1998); (ix) July insolation at 60 °N (W/m^2) (Berger and Loutre, 1991).

composition of the groundwater that feeds Lake Khall may have became more saline, and this event may have caused the final decline in substantial numbers of the ostracod *Candona* sp. Therefore it seems likely that the region underwent a period of extreme drought, which led to a decline in ostracoda in general. The rapid increase in sedimentation rate was concurrent with small peaks in particle size, perhaps indicative of increased aeolian transport onto the lake.

5.3. Late Holocene variability

Between ca. 1.9–0.7 cal ka BP, taxa indicative of cold coniferous forest declined and steppe communities virtually disappeared from the record altogether, coincident with marked increases in warmest month temperature anomalies. This period in general was characterised by little vegetation compositional change, and stable input of catchment derived particles (Figs. 3, 5 and 7). Increased reconstructed summer and winter temperatures were likely linked to increased northern hemisphere temperatures, as inferred from the GRIP borehole (Dahl-Jensen et al., 1998) (Fig. 8). Elsewhere in the Lake Baikal region, steppe communities were also less common (Tarasov et al., 2007), while high biogenic silica concentrations within Lake Baikal sediments were indicative of high aquatic productivity (Prokopenko et al., 2007). Peak reconstructed summer temperatures occurred between 1.33 and 0.77 cal ka BP, coincident with the period known as both the Medieval Warm Period (MWP) and Medieval Climate Anomaly (MCA). This period is distinct because although temperatures in many regions were warm (Mann et al., 2009) precipitation anomalies were also apparent in many regions in the world (Stine, 1994), leading to severe drought in e.g. northern Europe (Helama et al., 2009) and North America (Seager and Burgman, 2011). In the Ol'khon region, precipitation anomalies were higher than the previous period of drought, but still lower than the present. One of the few stratified deposits in the Lake Baikal region was excavated at Sagan-Zaba and dated between 2.0 and 0.9 cal ka BP. These deposits were likely associated with pastoralists, and although we are not able to say if the evidence of pastoralism was linked to a particularly quiescent period of environmental change, warmer summer and milder winter temperatures may have been conducive to a pastoral way of life.

For a short period between ca. 0.77–0.45 cal ka BP, local climate in the Ol'khon region became wetter and substantially colder, leading to an increase in *P. sibirica*, *P. obovata* and sedge pollen. *P. obovata* (Siberian spruce) is characteristic of soils with elevated moisture content, and likely represents real increases in tree abundance close to the lake (Bezrukova et al., 2005). However, there did not appear to be a substantial influence on Lake Khall itself – Sr/Ca ratios continued to increase, while ostracods only showed small increases in concentration. It is noteworthy that candonids did not recolonise the lake in any substantial numbers, and that black coatings on the ostracod valves almost disappeared. On the basis of the EDS and laser Raman determinations detailed in Section 4.3, it was assumed that the coatings were organic and indicative of reducing conditions in the upper layers of the sediment following death of the ostracods. Blackened valves dominated the lower part of the core, and were less common above 0.68 cal ka BP, suggesting a significant change in the ventilation of the lake after this time. Further work still needs to be done to determine the nature of the black coatings. Wetter climate has also been reconstructed from peat bog sequences from the northern shore of Lake Baikal (Bezrukova et al., 2006), and further afield in the Eastern Sayan mountains (Mackay et al., 2012). This period is coincident with IRD-0 in North Atlantic sediments and attenuation of the EASM (Wang et al., 2005; Fig. 8), and is concurrent with the Little Ice Age. Young moraines, associated with re-advancing glaciers at this time, can be found in the Sayan Mountains (Ivanovsky and Panychev, 1978 in

Shahgedanova et al., 2002), indicative of cooler, regional environments (Krenke and Chernavskaya, 2002). Chironomid-inferred temperatures from lake ESM-1 in the Eastern Sayan Mountains also showed a distinct cooling (Mackay et al., 2012).

Since ca. AD 1845, the increase in deciduous forest was linked to increased pollen-inferred precipitation and pollen-inferred temperature anomalies of the coldest and warmest months. The most striking change in the palynological record however, is the rapid increase in *Pediastrum* algae. *Pediastrum* belongs to the Chlorophyceae green algae, and is often characteristic of more nutrient rich waters. Palaeoenvironmental interpretations from *Pediastrum* records in lake sediments are not straightforward. Several studies tie the presence of *Pediastrum* to high lake levels in the semi-arid regions of e.g. Inner Mongolia (Jiang et al., 2006) and NE Tibetan Plateau (Zhao et al., 2007). In southern Scandinavia, increased concentrations of *Pediastrum* coenobia occurred during periods of warmer climate and increased lacustrine productivity (Sarmaja-Korjonen et al., 2006; Panizzo et al., 2008). In Lake Khall, increasing *Pediastrum* was coincident with increases in temperature of the coldest month and annual precipitation. During this period there was a rapid increase in sediment accumulation rate, the fastest for the past 5 ka, concomitant with a rapid decline in low field initial magnetic susceptibility measurements. This suggests that there was a decline in magnetisable sediments, possibly related to increased organic content and presence of algal growth. The increase in *Pediastrum* sp. therefore is likely indicative of a more nutrient rich lake. Animal husbandry intensified in the Lake Baikal region at this time because of the influx of Russian settlers (Tarasov et al., 2007). Local populations later undertook tree-felling (Sizykh, 2007), and although there is limited pollen evidence of anthropogenic activities, impacts on lacustrine ecosystems could be expected.

6. Conclusions

A multiproxy study of a small, shallow lake in the Ol'khon region of Lake Baikal was undertaken to determine climatic and human impacts on the landscape over the mid- to late-Holocene. We could only relate the significant turnover in vegetation composition to climate variability, and we found no evidence for anthropogenic activity despite the region having a long history of pastoralism. Geochemical evidence suggested that Lake Khall was once more fresh than it is today, and that over the study period, groundwater feeding the lake became more saline. The change in chemical composition had a negative impact on aquatic fauna by 2 cal ka BP. Pollen-based reconstructions from Lake Kotokel, a satellite to Lake Baikal (Tarasov et al., 2009) and regional climate modelling (White and Bush, 2010) exhibited similar trends to reconstructions from Lake Khall. For example, general trends demonstrated a decline in atmospheric precipitation and increase in continentality. The decrease in precipitation was accompanied by the changes in its seasonality, i.e. late Holocene strengthening of Westerlies in the region caused relative increase in winter (snow) accumulation. This feature together with drier summer conditions favoured the spread of drought resistant Scots pine. Reconstructed cool, moist conditions during the Little Ice Age are consistent with other palaeolimnological records, highlighting the regional nature of the response. Proxy records from Lake Khall also show a period of relative stability concurrent with the Medieval Climate Anomaly and a period of abrupt change between 2.75 and 2.48 cal ka BP, concurrent with influence from IRD-2 event in the north Atlantic. Finally, although human impact could not be determined from the terrestrial pollen record, preserved *Pediastrum* colonies may be indicative of a major recent phase of human impact.

Acknowledgements

We gratefully acknowledge funding through the Baikal Archaeology Project, supported by the Major Collaborative Research Initiative (MCRI) programme of the Social Sciences and Humanities Research Council of Canada. Thanks are given to Cath D'Alton for help in preparing figures and to Holly Watson for undertaking magnetic susceptibility measurements and particle size analysis.

References

Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments, vol. 1. Kluwer, Dordrecht, pp. 171–203.

Atlas Baikala (Baikal Atlas), 1993. Federal Service of Surveying and Cartography, Moscow, 159 pp. (in Russian).

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10, 297–317.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Interscience, New-York, pp. 455–484.

Bezrukova, E.V., Abzaeva, A.A., Letunova, P.P., Kulagina, N.V., Vershinin, K.E., Belov, A.V., Orlova, L.A., Danko, L.V., Krapivina, S.M., 2005. Post-glacial history of Siberian spruce (*Picea obovata*) in the Lake Baikal area and the significance of this species as a paleo-environmental indicator. Quaternary International 136, 47–57.

Bezrukova, E.V., Belov, A.V., Abzaeva, A.A., Letunova, P.P., Orlova, L.A., Sokolova, L.P., Kalugina, N.V., Fisher, E.E., 2006. First high-resolution dated records of vegetation and climate changes on the Lake Baikal northern shore in the middle-late Holocene. Doklady Earth Sciences 411, 1331–1335.

Bezrukova, E.V., Krivonogov, S.K., Takahara, H., Letunova, P.P., Shichi, K., Abzaeva, A.A., Kalugina, N.V., Zabelina, Yu.S., 2008. Lake Kotokel as a stratotype for the Late Glacial and Holocene southeastern Siberia. Doklady Earth Sciences 420, 658–663.

Bezrukova, E.V., Tarasov, P.E., Solovieva, N., Krivonogov, S.K., Fiedal, F., 2010. Last glacial-interglacial vegetation and environmental dynamics in southern Siberia: chronology, forcings and feedbacks. Palaeogeography, Palaeoclimatology, Palaeoecology 296, 185–198.

Birks, H.J.B., 2007. Estimating the amount of compositional change in late-quaternary pollen stratigraphical data. Vegetation History and Archaeobotany 16, 197–202.

Birks, H.J.B., Gordon, A.D., 1985. Numerical Methods in Quaternary Pollen Analysis. Academic Press, London.

Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6, 457–474.

Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Processes and Landforms 26, 1237–1248.

Blyakharchuk, T.A., Wright, H.E., Borodavko, P.S., van der Knaap, W.O., Amman, B., 2004. Late Glacial and Holocene vegetational changes on the Ulagan high-mountain plateau, Altai Mountains, southern Siberia. Palaeogeography, Palaeoclimatology and Palaeoecology 209, 259–279.

Bobrov, A.E., Kuprianova, L.A., Litvintseva, M.V., Tarasevich, V.F., 1983. Sporae Pteridophytorum et Pollen Gymnospermarum Monocotyledonearumque. Florae Parties Europaeae USSR. Nauka, Leningrad (in Russian).

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial scale cycle in North Atlantic Holocene and glacial climates. Science 278, 1257–1266.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., Balling, N., 1998. Past temperatures directly from the Greenland Ice Sheet. Science 282, 268–271.

Demske, D., Heumann, G., Granoszewski, W., Nita, M., Mamakowa, K., Tarasov, P.E., Oberhänsli, H., 2005. Late glacial and Holocene vegetation and regional climate variability evidenced in high-resolution pollen records from Lake Baikal. Global and Planetary Change 46, 255–279.

Folk, R.L., Ward, W.C., 1957. Brazos river bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology 27, 3–26.

Gabriel, K.R., 2002. Goodness of fit of biplots and correspondence analysis. Biometrika 89, 423–436.

Goslar, T., Czernik, J., Goslar, E., 2004. Low-energy ^{14}C AMS in Poznan radiocarbon laboratory, Poland. Nuclear Instruments and Methods in Physics Research B 223–224, 5–11.

Guiot, J., 1990. Methodology of the last climatic cycle reconstruction from pollen data. Palaeogeography, Palaeoclimatology, Palaeoecology 80, 49–69.

Helama, S., Merilainen, J., Tuomenvirta, H., 2009. Multicentennial megadrought in northern Europe coincided with a global El Nino-Southern oscillation drought pattern during the Medieval Climate Anomaly. Geology 37, 175–178.

Holmes, J., Sayer, C.D., Liptrot, E., Hoare, D.J., 2010. Complex controls on ostracod palaeoecology in a shallow coastal brackish-water lake: implications for palaeosalinity reconstruction. Freshwater Biology 55, 2484–2498.

Jacobson Jr., G.L., Bradshaw, R.H.W., 1981. The selection of sites for paleovegetational studies. Quaternary Research 16, 80–96.
Jiang, W.Y., Guo, Z.T., Sun, X.J., Wu, H.B., Chu, G.Q., Yuan, B.Y., Hattée, C., Guiot, J., 2006. Reconstruction of climate and vegetation changes of Lake Bayanchagan (inner Mongolia): Holocene variability of the east Asian monsoon. Quaternary Research 65, 411–420.
Jollifer, I.T., 1986. Principal Components Analysis. Springer-Verlag, New York.
Juggins, S., 1991. ZONE, Version 1.2. University of Newcastle, Newcastle Upon Tyne, UK.
Juggins, S., 2007. C2 Version 1.5.1 Software for Ecological and Palaeoecological Data Analysis and Visualisation. Newcastle University, Newcastle upon Tyne, UK.
Krenke, A.N., Chernavskaya, M.M., 2002. Climate changes in the preinstrumental period of the last millennium and their manifestations over the Russian Plain. Isvestiya, Atmospheric and Oceanic Physics 38, S59–S79.
Krishnaswami, S., Lal, D., Martin, J.M., Meybeck, M., 1971. Geochronology of lake sediments. Earth and Planetary Science Letters 11, 407–414.
Kuprianova, L.A., Alyoshina, L.A., 1972. Pollen and Spores of the Plants of the Flora of the European Part of USSR. Nauka, Leningrad (in Russian).
Line, J.M., Birks, H.J.B., 1996. BSTICK Version 1.0. Unpublished Computer Program. Botanical Institute, University of Bergen, Bergen.
Lotter, A.F., Birks, H.J.B., 1993. The impact of the Laacher See tephra on terrestrial and aquatic ecosystems in the Black Forest, southern Germany. Journal of Quaternary Science 8, 263–276.
Mackay, A.W., Swann, G.E.A., Brewer, T., Leng, M.J., Morley, D.W., Piotrowska, N., Rioual, P., White, D., 2011. A reassessment of Lateglacial–Holocene diatom oxygen isotope records from Lake Baikal using a mass balance approach. Journal of Quaternary Science 26, 627–634.
Mackay, A.W., Bezrukova, E.V., Leng, M.J., Meaney, M., Nunes, A., Piotrowska, N., Self, A., Shchetnikov, A., Shilland, E., Taarasov, P., Wang, L., White, D., 2012. Aquatic ecosystem responses to Holocene climate change and biome development in boreal central Asia. Quaternary Science Reviews 41, 119–131.
Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science 326, 1256–1260.
Marshall, F.C., 1969. Lower and Middle Pennsylvanian Fusulinids from the Bird Spring Formation near Mountain Springs Pass, Clark County, Nevada. In: Brigham Young University Geology Studies, vol. 16, pp. 97–154.
Mischke, S., Zhang, C., Börner, A., Herzschuh, U., 2010. Lateglacial and Holocene variation in Aeolian sediment flux over the northeastern Tibetan Plateau recorded by laminated sediments of a saline meromictic lake. Journal of Quaternary Science 25, 162–177.
Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, Osney Mead, Oxford.
New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Climate Research 21, 1–25.
Nielsen, H., Sørensen, I., 1992. Taxonomy and stratigraphy of lateglacial *Pediastrum* taxa from Lysmosen, Denmark – a preliminary study. Review of Palaeobotany and Palynology 74, 55–75.
Nomokonova, T., Losely, R.J., Goriunova, O.I., Weber, A., 2013. A freshwater old carbon offset in Lake Baikal, Siberia and problems with the radiocarbon dating of archaeological sediments: evidence from the Sagan Zaba II site. Quaternary International 290–291, 110–125.
Nomokonova, T., Losely, R.J., Weber, A., Goriunova, L.I., Novikov, A.G., 2010. Late Holocene subsistence practices among cis-Baikal pastoralists, Siberia: zooarchaeological insights from Sagan-Zaba II. Asian Perspectives 49, 157–179.
Overpeck, J.T., Webb III, T., Prentice, I.C., 1985. Quantitative interpretation of fossil pollen spectra, dissimilarity coefficients and the method of modern analogs. Quaternary Research 23, 87–108.
Panizzo, V.N., Jones, V.J., Birks, H.J.B., Boyle, J.F., Brooks, S.J., Leng, M.J., 2008. A multiproxy palaeolimnological investigation of Holocene environmental change, between c. 10 700 and 7200 years BP, at Holebudalen, southern Norway. The Holocene 18, 805–817.
Prentice, I.C., Guiot, J., Huntley, B., Jolly, D., Cheddadi, R., 1996. Reconstructing biomes from palaeocological data: a general method and its application to European pollen data at 0 and 6 ka. Climate Dynamics 12, 185–194.
Prokopenko, A.A., Khursevich, G.K., Bezrukova, E.V., Kuzmin, M.I., Boes, X., Williams, D.F., Fedenya, S.A., Kulagina, N.V., Letunova, P.P., Abzaeva, A.A., 2007. Paleoenvironmental proxy records from Lake Hovsgol, Mongolia, and a synthesis of Holocene climate change in the Lake Baikal watershed. Quaternary Research 68, 2–17.
Ptitsyn, A.B., Reshetova, S.A., Babich, V.V., Daryin, A.V., Kalugin, I.A., Ovchinnikov, D.V., Panizzo, V., Myglan, V.S., 2010. Palaeoclimate chronology and aridization tendencies in the Transbaikalia for the last 1900 years. Geography and Natural Resources 31, 144–147.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.
Robbins, J.A., 1978. Geochemical and geophysical applications of radioactive lead. In: Nriagu, J.O. (Ed.), Biogeochemistry of Lead in the Environment. Elsevier Scientific, Amsterdam, pp. 285–393.
Sarmaja-Korjonen, K., Seppänen, A., Bennike, O., 2006. *Pediastrum* algae from the classic late glacial Bølling Sø site, Denmark: response of aquatic biota to climate change. Review of Palaeobotany and Palynology 138, 95–107.
Seager, R., Burgman, R.J., 2011. Medieval hydroclimate revisited. PAGES News 19, 10–12.
Seppä, H., Bennett, K.D., 2003. Quaternary pollen analysis: recent progress in palaeoecology and palaeoclimatology. Progress in Physical Geography 27, 548–579.
Shahgedanova, M., Mikhailov, N., Larin, S., Bredikhin, A., 2002. The mountains of southern Siberia. In: Shahgedanova, M. (Ed.), The Physical Geography of Northern Eurasia. OUP, Oxford, pp. 314–349.
Shichi, K., Takahara, H., Krivonogov, S.K., Bezrukova, E.V., Kashiwaya, K., Takehara, A., Nakamura, T., 2009. Late Pleistocene and Holocene vegetation and climate records from Lake Kotokel, central Baikal region. Quaternary International 205, 98–110.
Sizykh, A.P., 2007. Models of taiga-steppe communities on the western coast of Lake Baikal. Russian Journal of Ecology 38, 234–237.
Sklyarov, E.V., Solotchina, E.P., Vologina, E.G., Ignatova, N.V., Izokh, O.P., Kulagina, N.V., Sklyarova, O.A., Solotchin, P.A., Stolpovskaya, V.N., Ukhova, N.N., Federovskii, V.S., Khlystov, O.M., 2010. Detailed Holocene climate record from the carbonate section of saline Lake Tsagan-Tyrm (West Baikal area). Russian Geology and Geophysics 51, 237–258.
Sklyarova, O.A., Sklyarov, E.V., Fedorovskii, V.S., 2002. Structural control of location and water chemistry of lakes and springs in the Ol'khon region. Russian Geology and Geophysics 43, 732–745.
Stine, S., 1994. Extreme and persistent drought in California and Patagonia during medieval time. Nature 369, 546–549.
Sugita, S., 1994. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. Journal of Ecology 82, 881–897.
Tarasov, P., Granoszewski, W., Bezrukova, E., Brewer, S., Nita, M., Abzaeva, A., Oberhänsli, H., 2005. Quantitative reconstruction of the last interglacial vegetation and climate based on the pollen record from Lake Baikal, Russia. Climate Dynamics 25, 625–637.
Tarasov, P., Bezrukova, E., Karabanov, E., Nakagawa, T., Wagner, M., Kulagina, N., Letunova, P., Abzaeva, A., Granoszewski, W., Riedel, F., 2007. Vegetation and climate dynamics during the Holocene and Eemian interglacials derived from Lake Baikal pollen records. Palaeogeography, Palaeoclimatology and Palaeoecology 252, 440–457.
Tarasov, P.E., Bezrukova, E.V., Krivonogov, S.K., 2009. Late Glacial and Holocene changes in vegetation cover and climate in southern Siberia derived from a 15 kyr long pollen record from Lake Kotokel. Climate of the Past 5, 285–295.
ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO Reference Manual and User's Guide to CANOCO for Windows: Software for Canonical Community Ordination Version 4.5. Microcomputer Power, Ithaca, New York.
Wang, Y., Cheng, H., Edwards, R.L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M.J., Dykoski, C.A., Li, X., 2005. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science 308, 854–857.
Weber, A.W., Link, D.W., Katzenberg, M.A., 2002. Hunter-gather culture change and continuity in the middle Holocene of the cis-Baikal, Siberia. Journal of Anthropological Archaeology 21, 230–299.
Weber, A.W., Katzenberg, M.A., Schurr, T.G. (Eds.), 2010. Prehistoric Hunter-gatherers of the Baikal Region, Siberia: Bioarchaeological Studies of Past Lifeways. University of Pennsylvania Press, Philadelphia, USA.
White, D., Bush, A.B.G., 2010. Holocene climate, environmental variability and Neolithic biocultural discontinuity in the Lake Baikal region. In: Weber, A.W., Katzenberg, M.A., Schurr, T.G. (Eds.), Prehistoric Hunter-gatherers of the Baikal Region, Siberia: Bioarchaeological Studies of Past Lifeways. University of Pennsylvania Museum Press, Pennsylvania, pp. 1–26.
Wünneman, B., Demske, D., Tarasov, P., Kotlia, B.S., Reinhardt, C., Bloemendal, J., Diekmann, B., Hartmann, K., Krois, J., Riedal, F., Arya, N., 2010. Hydrological evolution during the last 15 kyr in the Tso Kar lake basin (Ladakh, India), derived from geomorphological, sedimentological and palynological records. Quaternary Science Reviews 29, 1138–1155.
Zhao, Y., Yu, Z., Chen, F., Ito, E., Zhao, C., 2007. Holocene vegetation and climate history at Hurleg Lake in the Qaidam Basin, northwest China. Review of Palaeobotany and Palynology 145, 275–288.